

## X-RAY OBSERVATIONS OF SUPERNOVA REMNANTS AS DISTANCE INDICATORS

NAMIR E. KASSIM,<sup>1</sup> PAUL HERTZ,<sup>2</sup> SCHUYLER D. VAN DYK,<sup>1,3</sup> AND KURT W. WEILER<sup>1</sup>

Received 1994 February 16; accepted 1994 March 17

### ABSTRACT

We investigate whether *ROSAT* observations of thermal X-ray emission from shell-type supernova remnants (SNRs) can be used to constrain their distances. The most critical assumption is that the initial kinetic energy ( $\epsilon_0$ ) of a supernova (SN) explosion is a constant at  $\epsilon_0 = 10^{51}$  ergs; however, the derived distance ( $D$ ) is only weakly dependent on  $\epsilon_0$  ( $D \propto \epsilon_0^{0.4}$ ). We evaluate this technique by applying it to SNRs with independently determined distances, and our initial results indicate good agreement. We conclude that the *ROSAT* all-sky survey may be used to establish, for the first time, a set of good distance estimates to a large number of extended, shell-type SNRs. The energy range of *ROSAT* is well suited for this purpose, since most shell-type SNRs have thermal X-ray spectra which peak within the *ROSAT* PSPC energy range of 0.1–2.4 keV.

*Subject headings:* supernova remnants — X-rays: general

### 1. INTRODUCTION

SNRs are important in Galactic astrophysics because they are the major source of energy input to the interstellar medium, serve as the site of cosmic-ray acceleration and play a role in triggering star formation. Unlike H II regions, whose distances can be constrained kinematically, Galactic SNRs have poorly determined distances. Of the currently known  $\sim 180$  Galactic remnants, only  $\sim 15\%$  have distance determinations and only a limited subset of these are likely to be reliable (Green 1984). Most methods of establishing distances to SNRs are either difficult and uncertain (H I absorption) or are too inexact to be useful (e.g., the “ $\Sigma$ -D” relation) (Green 1984). We describe how soft X-ray observations, such as those made by the German X-ray observatory *ROSAT* (Trümper 1983), can be used to estimate distances to many shell-type SNRs. We have already applied this procedure to G326.3–1.8 (Kassim, Hertz, & Weiler 1993), and we apply it here to a number of SNRs with independently established distances in order to test the procedure’s validity.

### 2. THEORY

The Sedov equations, which describe the dynamics of shell-type SNR expansion during the adiabatic phase, can be combined (Kassim et al. 1993) to solve for a “Sedov” distance  $D_S$  to the SNR in kiloparsecs as

$$D_S = 8.7 \times 10^6 \epsilon_0^{0.4} P(\Delta E, T)^{0.2} \theta^{-0.6} F_{x_0}^{-0.2} T^{-0.4}. \quad (1)$$

Here  $\epsilon_0$  is the initial energy of the SN explosion (thermal plus kinetic) in units of  $10^{51}$  ergs,  $\theta$  is the observed angular diameter of the SNR shell in arcminutes,  $F_{x_0}$  is the measured X-ray flux corrected for interstellar (and/or intergalactic) absorption in units of  $\text{ergs s}^{-1} \text{cm}^{-2}$ , and  $T$  is the measured thermal temperature of the X-ray-emitting gas in K. The tabulated analytical function  $P(\Delta E, T)$  in units of  $\text{ergs cm}^3 \text{s}^{-1}$  describes the power emitted by hot electrons in a low-density plasma via free-free emission (Tucker & Koren 1971a, b) and is a function

of both the energy band of the emission and the temperature of the plasma. The uncertainties in determining  $D_S$  are dominated by the assumptions inherent in applying equation (1) and not by measurement errors in the temperature, interstellar absorption, and flux as determined from *ROSAT* PSPC X-ray spectra, as was often the case with pre-*ROSAT* X-ray observations.

The key assumptions of the Sedov analysis reflected by equation (1) are (1) the SNR shell is in the adiabatic expansion phase; (2) the measured X-ray temperature gives a reliable estimate of the SN shock velocity; and (3)  $\epsilon_0 = 1$  (in units of  $10^{51}$  ergs) is approximately correct for all SNe. Assumption (1) is the only one which can be checked self-consistently. A calculation of the swept-up mass ( $M_{su}$ ) can be used to test whether a SNR has passed the free-expansion phase and entered the adiabatic expansion phase (Kassim et al. 1993), and relations have been developed (Cox 1972; McKee 1982; Cioffi, McKee, & Bertschinger 1988) to calculate if the SNR has entered either the pressure-driven or radiative phases.

Unfortunately, neither assumptions 2 nor 3 can be firmly established on either theoretical or observational grounds. Calculations of Type I SNe show that  $\epsilon_0$  only varies over the range 0.9–1.5 (Nomoto, Thielemann, & Yokoi 1984), but there are no generally accepted ways of estimating the energy of Type II events. With the total energy released in the gravitational collapse of a star during a SN explosion of  $\sim 10^{53}$  ergs, the assumed thermal plus kinetic energy  $\epsilon_0$  of  $10^{51}$  ergs is only  $\sim 1\%$  of the total. Since the efficiency of transforming gravitational energy into thermal and kinetic forms is not well understood and could be highly variable, assumption 3 may be only roughly correct. Assumption 2 is related to complex issues involving the degree of thermalization of the kinetic energy in the shock, the extent of the equilibrium between ion and electron energies, and the equilibration of the electron velocity distribution and ionization nonequilibrium. These areas are directly related to poorly determined theories of SNe and strong shocks. Also, the detection of X-rays from cooler gas behind the shock front and in the remnant interior may lead to a measured X-ray temperature which is less than the shock temperature (Rappaport et al. 1974), and hence an underestimate of the SN shock velocity. We also note that the assumption of solar abundances in the line-dominated X-ray spectra could lead to errors in the X-ray temperature when measured

<sup>1</sup> Code 7215, Remote Sensing Division, Naval Research Laboratory, Washington, DC 20375-5351.

<sup>2</sup> Code 7621, E. O. Hulbert Center for Space Research, Naval Research Laboratory, Washington, DC 20375-5352.

<sup>3</sup> Current address: Department of Astronomy, University of California, Berkeley, CA 94720.

<b>Report Documentation Page</b>			Form Approved OMB No. 0704-0188		
<p>Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p>					
1. REPORT DATE <b>JUN 1994</b>	2. REPORT TYPE	3. DATES COVERED <b>00-00-1994 to 00-00-1994</b>			
4. TITLE AND SUBTITLE <b>X-Ray Observations of Supernova Remnants as Distance Indicators</b>			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Naval Research Laboratory, Code 7213, 4555 Overlook Avenue, SW, Washington, DC, 20375</b>			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES <b>3</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

with a low spectral resolution device like the *ROSAT* PSPC (Hughes 1994).

### 3. APPLICATION

Fortunately, we can conduct an empirical test of the validity of the "Sedov" distance as expressed in equation (1) by applying it to *ROSAT* data for shell-type SNRs with relatively well-established independent distance estimates. Table 1 summarizes the data for our sample. All values of  $T$  and  $F_{x0}$  (col. [2]–[3]) are from *ROSAT* observations (energy range  $\sim 0.1$ – $2.4$  keV) as referenced in column (9), except for the LMC SNR N49 (Gordon et al. 1993). The mainly radio-determined angular sizes ( $\theta$ ; col. [4]) are obtained from Green's SNR catalog (Green 1990, 1991, 1994) for the Galactic SNRs, otherwise as referenced in column (9). The radio morphology is known to be a good tracer of the blast wave, while the X-ray morphology can be centrally condensed even for shell-type SNRs (Dickel et al. 1994; Jones, Smith, & Angellini 1993; Rho et al. 1994). The swept-up mass ( $M_{su}$ , col. [5]) is determined by solving the Sedov equation (see, e.g., Kassim et al. 1993)

$$M_{su} = 3.6 \times 10^{-9} P(\Delta E, T)^{-0.5} \theta^{1.5} F_{x0}^{0.5} D^{2.5}, \quad (2)$$

with the assumption that the distance,  $D$ , is given by the independent distance estimate ( $D_i$ , col. [7]); no assumption about the explosion energy is required.

The Sedov distances ( $D_S$ , col. [6]) are obtained from equation (1). The independent distances ( $D_i$ , col. [7]) are obtained from the Green SNR catalog (Green 1990, 1991, 1994) when available, otherwise as referenced in column (9). The ratio  $D_S/D_i$  (col. [8]) is also listed, and the two distance estimates are plotted against one another in Figure 1 for all of the remnants except G18.9–1.1, which is probably not in the Sedov phase (see below). The error bars represent statistical uncertainties only and are based on propagating measurement errors for  $T$ ,  $\theta$ ,  $F_{x0}$ , and  $D_i$  where available; otherwise we use canonical uncertainties of 10% for  $\theta$ , 25% for  $T$  and  $D_i$ , and the smaller

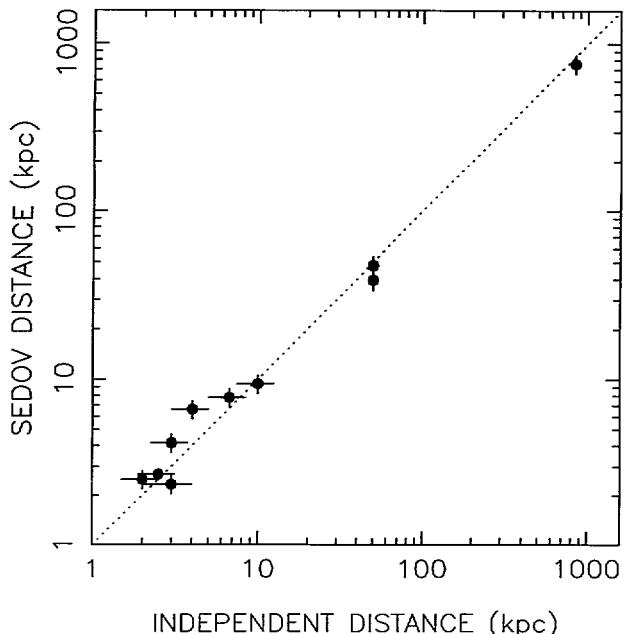


FIG. 1.—Plot of the X-ray determined Sedov distance  $D_S$  vs. the independently determined distance  $D_i$  for seven Galactic and three extragalactic shell-type SNRs. Error bars represent statistical uncertainties only (see text). The data are clearly well fitted by the dotted line representing  $D_S = D_i$ .

of 20% and  $2 \times 10^{-12}$  ergs cm $^{-2}$  s $^{-1}$  for  $F_{x0}$ . Note that the measurement errors from *ROSAT*-determined Sedov distances are smaller than the typical uncertainty in H I distance determinations for Galactic SNRs. Figure 1 shows clearly that  $D_S = D_i$  is consistent to within the errors.

### 4. DISCUSSION

With the single exception of G18.9–1.1, discussed below, all SNRs listed in Table 1 have  $M_{su} > 20 M_\odot$ , implying that they

TABLE 1  
OBSERVED AND DERIVED RADIO AND X-RAY PARAMETERS FOR 11 SUPERNOVA REMNANTS

SNR (1)	$kT^a$ (keV) (2)	$F_{x0}^b$ (ergs s $^{-1}$ cm $^{-2}$ ) (3)	$\theta^b$ (') (4)	$M_{su}^c$ ( $M_\odot$ ) (5)	$D_S^d$ (kpc) (6)	$D_i^e$ (kpc) (7)	$D_S/D_i$ (8)	Reference (9)
G18.9–1.1 .....	0.43	2.8E–11	33	4.4	8.4	2.0	4.2	1
G160.9+2.6 .....	0.61	1.0E–10	130	64	2.5	2.0 <sup>f</sup>	1.3	2
G156.2+5.7 .....	0.50	1.9E–10	108	115	2.7	2.5	1.1	3
G34.7–0.4 .....	2.8	2.5E–10	31	46	2.3	3.0 <sup>f</sup>	0.8	4
G132.7+1.3 .....	0.16	9.3E–10	80	191	4.2	3.0 <sup>f</sup>	1.4	2
G296.1–0.7 .....	0.20	6.3E–10	33	98	6.6	4.0	1.7	5
G53.6–2.2 .....	0.27	1.9E–10	28	174	7.8	6.7 <sup>f</sup>	1.2	2
G33.6+0.1 .....	1.3	4.3E–11	10	62	9.4	10 <sup>f</sup>	0.9	6
N49 .....	0.65	8.0E–11	1.1	119	48	50 <sup>g</sup>	1.0	7
0540–69.3 .....	5.5	2.3E–12	0.9	23	39	50 <sup>g</sup>	0.8	8
013022+30233 .....	0.33	4.8E–13	0.1	272	758	840 <sup>h</sup>	0.9	7

<sup>a</sup> All *ROSAT* determined except for the LMC SNR N49 (Gordon et al. 1993).

<sup>b</sup> Radio-determined (Green 1990, 1991, 1994) for Galactic SNRs, otherwise as referenced in col. (9).

<sup>c</sup> All swept-up masses are determined from the Sedov equations assuming  $D_i$  is the correct distance (see text).

<sup>d</sup> Sedov distance from eq. (1).

<sup>e</sup> As noted; otherwise as referenced in (9).

<sup>f</sup> From the Green SNR catalog (Green 1990, 1991, 1994).

<sup>g</sup> Adopted distance to the LMC (Panagia et al. 1991).

<sup>h</sup> Adopted distance to M33 (Freedman, Wilson, & Madore 1991).

REFERENCES.—(1) Aschenbach et al. 1991; (2) Saken et al. 1994; (3) Pfeffermann, Aschenbach, & Predehl 1991; (4) *ROSAT* Archive; (5) Hwang & Markert 1994; (6) Seward & Velusamy 1993; (7) Gordon et al. 1993; (8) Seward & Harnden 1994.

have passed the free-expansion phase. Also, we have calculated the radii at which the SNRs in Table 1 are expected to enter the pressure driven and radiative phases and, under the criteria of Burrows et al. (1993) with  $\epsilon_0 = 1$ , none has yet evolved beyond the adiabatic phase.

While the correlation between  $D_S$  and  $D_i$  appears well defined for all SNRs in Figure 1, Table 1 includes one object, G18.9–1.1, which illustrates that the technique is not applicable to SNRs which have not fully evolved to the Sedov stage. An independent distance estimate of  $\sim 2$  kpc from H I observations has been used by Aschenbach et al. (1991) with the Sedov assumption to calculate  $\epsilon_0 = 0.05$ . However, the estimated swept-up mass for this SNR is only  $4.4 M_\odot$ . Since existing models for SN ejected masses range from  $\sim 1\text{--}5 M_\odot$  (Woosley et al. 1994), it is quite likely that G18.9–1.1 is still in transition from the free-expansion to the Sedov stage, and therefore the Aschenbach et al. (1991) calculation of the explosion energy may not be valid. For the same reason, our distance estimating technique probably does not apply to G18.9–1.1, and we have excluded it from Figure 1.

The average value of  $D_S/D_i$  for the remaining 10 SNRs included in Figure 1 is 1.1, with a standard deviation of  $\sim 0.3$ . To within the errors, this implies that, for SNRs in the Sedov phase, our X-ray-based distance estimates are in agreement with distances obtained by other methods and the technique can likely be applied to the many SNRs observed with *ROSAT* for which independent distance estimates are not available.

## 5. SUMMARY

Our initial test comparing *ROSAT* derived “Sedov” distances with independent distance estimates for shell-type SNRs indicates the modern X-ray measurements are a powerful tool for obtaining distances to large numbers of shell-type SNRs. While several key assumptions cannot be rigorously justified on theoretical grounds at this time, the empirical conclusion is that the method offers a useful distance estimate in the absence of other data. High-resolution X-ray spectra of SNRs, such as those obtainable with the Japanese *ASCA* (*Astro-D*) satellite, will test our ability to measure plasma temperatures in line dominated plasmas with a low-resolution spectrometer, such as the *ROSAT* PSPC. As the X-ray parameters become available for many more SNRs from the *ROSAT* all-sky survey, further tests of the method will better define its accuracy and utility.

The authors would like to thank D. Burrows and N. Panagia for useful comments and suggestions regarding this paper. Basic research in Radio Interferometry at the Naval Research Laboratory is supported by the Office of Naval Research through funding document number N00014-93-WX-35012, under NRL work unit 2567.

## REFERENCES

- Aschenbach, B., Brinkmann, W., Pfeffermann, E., Fürst, E., & Reich, W. 1991, *A&A*, 246, L32
- Burrows, D. N., Singh, K. P., Nousek, J. A., Garmire, G. P., & Good, J. 1993, *ApJ*, 406, 97
- Cioffi, D. F., McKee, C. F., & Bertschinger, E. 1988, *ApJ*, 334, 252
- Cox, D. P. 1972, *ApJ*, 178, 159
- Dickel, J. R., Murphy, R., Chu, Y., & Goscha, D. L. 1994, in Proc. 1st Ann. *ROSAT* Science Symp. and Data Analysis Workshop, ed. E. M. Schlegel & R. Petre (New York: AIP), in press
- Freedman, W. L., Wilson, C., & Madore, B. 1991, *ApJ*, 372, 455
- Gordon, S. M., Kirshner, R. P., Duric, N., & Long, K. S. 1993, *ApJ*, 418, 743
- Green, D. A. 1984, *MNRAS*, 209, 449
- . 1990, *Ap&SS*, 148, 3
- . 1991, *PASP*, 103, 209
- . 1994, in *Supernovae and Supernova Remnants*, ed. R. McCray & Z. Wang, in press
- Hughes, J. P. 1994, private communication
- Hwang, U., & Markert, T. H. 1994, *ApJ*, in press
- Jones, L. R., Smith, A., & Angellini, L. 1993, *MNRAS*, 265, 631
- Kassim, N. E., Hertz, P., & Weiler, K. W. 1993, *ApJ*, 419, 733
- McKee, C. F. 1982, in *Supernovae: A Survey of Current Research*, ed. M. J. Rees & R. J. Stoneham (Dordrecht: Reidel), 433
- Nomoto, K., Thielemann, F. K., & Yokoi, K. 1984, *ApJ*, 286, 644
- Panagia, N., Gilmozzi, R., Macchett, F., Adorf, H.-M., & Kirshner, R. P. 1991, *ApJ*, 380, L23
- Pfeffermann, E., Aschenbach, B., & Predehl, P. 1991, *A&A*, 246, L28
- Rappaport, S., Doxsey, R., Solinger, A., & Borken, R. 1974, *ApJ*, 194, 329
- Rho, J.-H., Petre, R., Schlegel, E. M., & Hester, J. 1994, *ApJ*, in press
- Saken, J. M., Long, K. S., Blair, W. P., Winkler, P. F., & DeChristopher, B. M. 1994, in Proc. 1st Ann. *ROSAT* Science Symp. and Data Analysis Workshop, ed. E. M. Schlegel & R. Petre (New York: AIP), in press
- Seward, F. D., & Harnden, F. R. 1994, *ApJ*, 421, 581
- Seward, F. D., & Velusamy, T. 1993, *BAAS*, 25, 1421
- Trümper, J. 1983, *Adv. Space Res.*, 2, 241
- Tucker, W. H., & Koren, M. 1971a, *ApJ*, 168, 283
- . 1971b, *ApJ*, 170, 621
- Woosley, S. E., Eastman, R. G., Weaver, T. A., & Pinto, P. A. 1994, *ApJ*, in press